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[54] **INTEGRATED CIRCUIT HAVING AN ON CHIP THERMAL CIRCUIT REQUIRING ONLY ONE DEDICATED INTEGRATED CIRCUIT PIN AND METHOD OF OPERATION**

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[52] **U.S. Cl.** ..... **257/467**; 257/776; 257/777; 338/22 R

[58] **Field of Search** 257/467, 776, 777; 338/22

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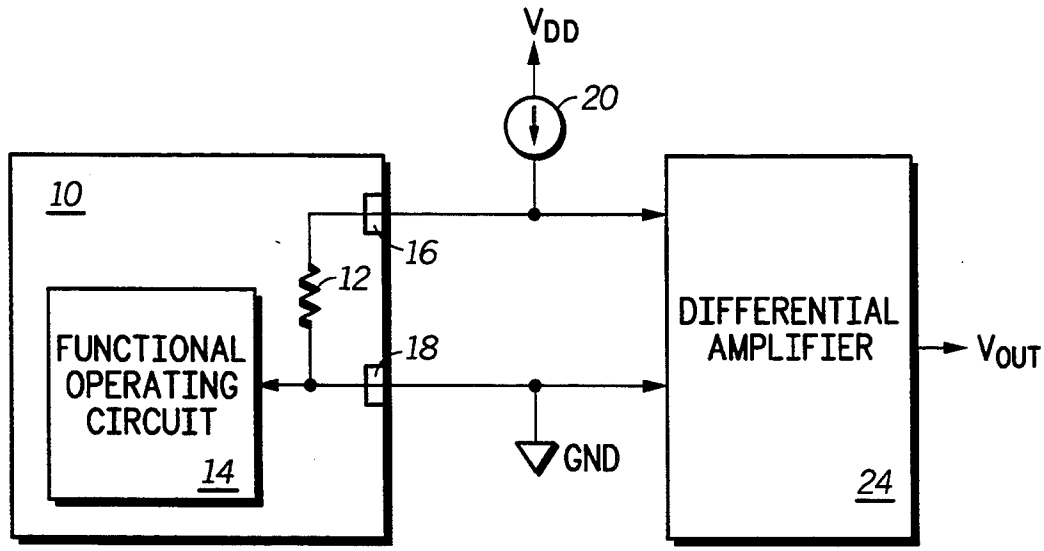
[57] **ABSTRACT**

An integrated circuit implements an on chip thermal circuit (**12**) for measuring temperature of an operating integrated circuit die (**10**) by requiring only one dedicated integrated circuit pin (**16**). A second integrated circuit pin (**18**) is utilized but is also connected directly connected to other circuitry (**14**) on the integrated circuit and is used by the other circuitry at the same time that the integrated circuit die temperature is being measured. In one form, the second integrated circuit pin is a ground terminal. Error voltages coupled to the ground terminal may be removed from the temperature calculation by an external differential amplifier (**24**).

14 Claims, 1 Drawing Sheet



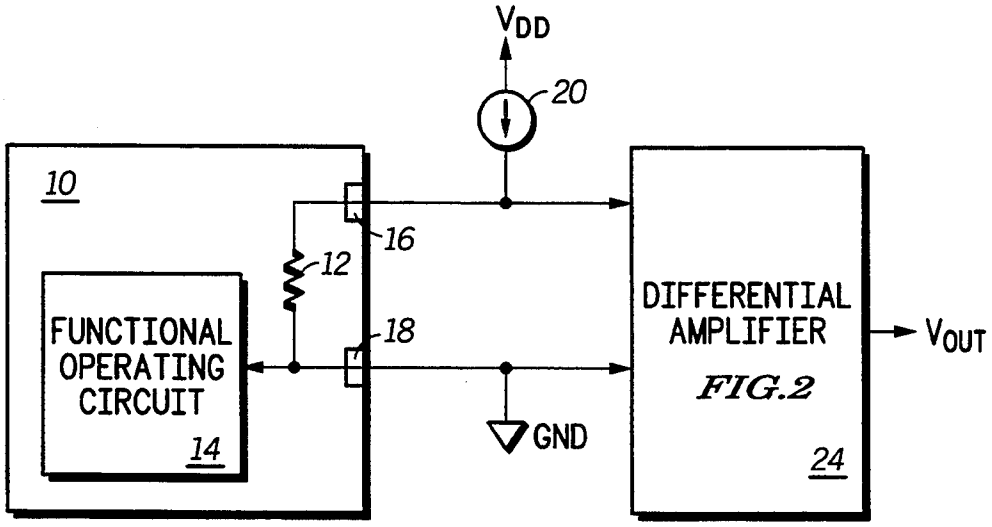


FIG.2

FIG.1

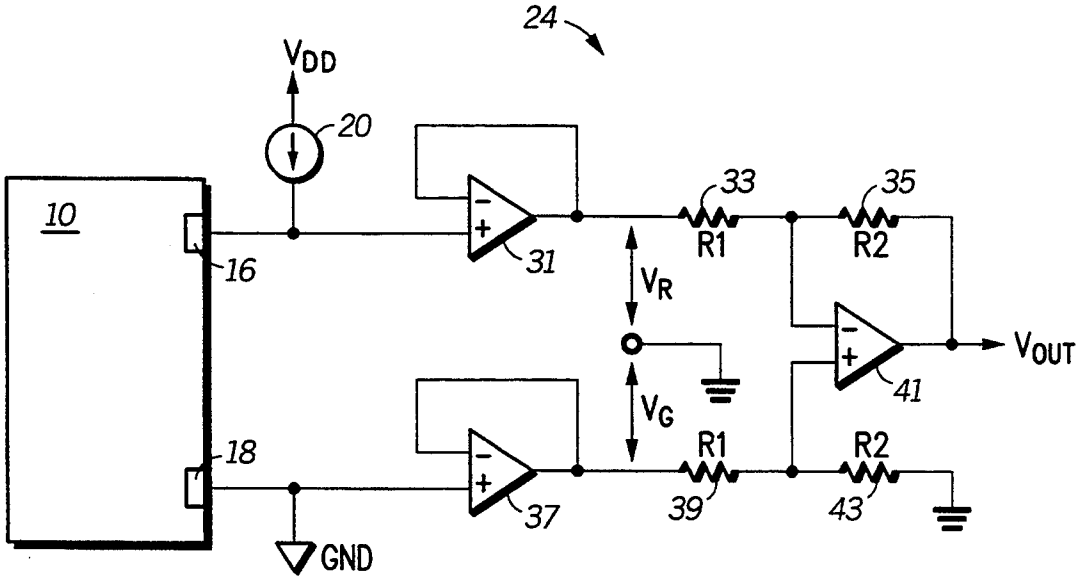


FIG.2

INTEGRATED CIRCUIT HAVING AN ON CHIP THERMAL CIRCUIT REQUIRING ONLY ONE DEDICATED INTEGRATED CIRCUIT PIN AND METHOD OF OPERATION

FIELD OF THE INVENTION

The present invention generally relates to integrated circuits, and more particularly, to the monitoring of thermal characteristics of an operating integrated circuit.

BACKGROUND OF THE INVENTION

An important operating characteristic of an integrated circuit is the temperature of the integrated circuit's die when the integrated circuit is fully powered and in a normal operating mode of operation. Such a temperature measurement is often desired at a final package test when the integrated circuit is in the same form as will be used by an end user. To satisfy this need, others have used an on-chip resistor connected to two dedicated external pins of the integrated circuit. The external pins have no other function than to implement the temperature measurement function. An example of an integrated circuit having two dedicated pins for temperature measurement of the integrated circuit die is the MC88110 reduced instruction set microprocessor.

The temperature of the integrated circuit having an on-chip resistor is measured by using a current source reference and forcing a known current thru the known resistance of the on-chip resistor. A resulting voltage across the two dedicated integrated circuit pins is then measured. The resulting voltage is proportional to the temperature of the operating integrated circuit. In other words, as the temperature of the operating integrated circuit die varies, the resistance varies proportionately which results in a proportional change in voltage measured across the two dedicated integrated circuit pins. The two dedicated integrated circuit pins are required in order to isolate internally generated noise and other circuit parameters from the two integrated circuit pins. Any voltage, current, resistance or impedance which is coupled to the two integrated circuit pins from internal to the integrated circuit will modify the voltage potential between the two integrated circuit pins and result in an incorrect temperature measurement. However, the price of two dedicated integrated circuit pins to implement a measurement function is costly, even in the most advanced very large scale integrated circuits.

Another type of integrated circuit which uses a plurality of resistors connected between the integrated circuit's external pins is a resistor network integrated circuit. However, this type of integrated circuit functions only to provide a user with a plurality of possible resistance values depending upon which pins of the integrated circuit are connected. No other operating circuitry is typically implemented in such circuits.

Yet another known type of integrated circuit which provides a signal from which an operating die temperature may be derived utilizes a significant amount of dedicated internal circuitry, such as an analog-to-digital (A/D) circuit and a storage register, to provide the signal at a single dedicated output pin of the integrated circuit. The additional internal circuitry which is required to implement this temperature measurement function is often prohibitive in many large scale integration designs.

SUMMARY OF THE INVENTION

In accordance with one form of the invention, there is provided an integrated circuit having an on chip thermal circuit requiring only one dedicated integrated circuit pin and a method of implementing a single pin on chip thermal circuit in an integrated circuit. The integrated circuit comprises a die and a first integrated circuit pin which is dedicated solely for use with the on chip thermal circuit. A second integrated circuit pin is also provided. An integrated circuit die thermal sensing circuit is located on the die and directly connected to the first integrated circuit pin and to the second integrated circuit pin. The integrated circuit die thermal sensing circuit comprises a material which has a physical characteristic which varies in a manner proportional to variation of temperature of the material. A functional operating circuit is located on the die and is connected directly to the second integrated circuit pin. The functional operating circuit performs a predetermined operating function within the integrated circuit at the same time the integrated circuit die thermal sensing circuit provides an output signal which indicates an operating temperature of the die. The second integrated circuit pin is used by both the integrated circuit die thermal sensing circuit and the functional operating circuit.

These and other features, and advantages, will be more clearly understood from the following detailed description taken in conjunction with the accompanying drawings. It is important to point out that there may be other embodiments of the present invention which are not specifically illustrated.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** illustrates in block diagram form an on-chip die thermal sensing circuit in accordance with the present invention; and

FIG. **2** illustrates in partial schematic form the differential amplifier of FIG. **1**.

DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

Illustrated in FIG. **1** is an integrated circuit die **10** in accordance with the present invention. Although not fully illustrated as a packaged integrated circuit for purposes of illustrating the present invention, integrated circuit die **10** should be considered as a fully encapsulated die in a completed integrated circuit chip. Integrated circuit die **10** generally has a die thermal sensing circuit **12**, a functional operating circuit **14**, a first integrated circuit pin **16**, and a second integrated circuit pin **18**. Also illustrated is a constant current source **20** and a differential amplifier **24**.

In the illustrated form, die thermal sensing circuit **12** is implemented as a resistor having a first terminal connected to first integrated circuit pin **16** and having a second terminal connected to second integrated circuit pin **18**. In the illustrated form, the second integrated circuit pin **18** is a ground reference pin of integrated circuit die **10**. Functional operating circuit **14** has a terminal connected directly to the second integrated circuit pin **18**, thereby making the second integrated circuit pin a common integrated circuit pin which is common to both the die thermal sensing circuit **12** and the functional operating circuit **14**. A constant current source **20** has a first terminal connected to a power supply voltage, such as V_{DD}, and has a second terminal connected to both the first integrated circuit pin **16** and

a first input of differential amplifier **24**. A second input of differential amplifier **24** is connected to the second integrated circuit pin **18**. An output of differential amplifier **24** provides an output voltage, Vout, which is referenced to a ground reference terminal and is proportional to temperature.

In operation, an operating temperature of integrated circuit die **10** may be accurately measured while circuit die **10** is fully operational. Further, this function only requires one dedicated integrated circuit pin, the first integrated circuit pin because the second integrated circuit pin is used concurrently by the functional operating circuit **14**. Functional operating circuit **14** performs a predetermined operating function within the integrated circuit **10** at the same time the present invention is utilized to determine the die operating temperature. Examples of the functionality of operating circuit **14** might include an execution unit, digital logic circuitry, address translation circuitry, a memory, etc.. In one form, the die thermal sensing circuit **12** is implemented as a resistor. If a metal resistor is utilized, a resistor may be formed which is susceptible to average temperature changes of the integrated circuit die **10** and which provides a temperature coefficient of approximately 1.2 Ohms/degree Centigrade. It should be well understood that other materials, such as polysilicon for example, may be used to implement die thermal sensing circuit **12**. As constant current source **20** provides a constant reference current to integrated circuit die **10**, a small predetermined voltage is developed across the resistance of die thermal sensing circuit **12**. The resistance of die thermal sensing circuit **12** is proportional to the temperature of the die in accordance with the following equation:

$$\text{Resistance of circuit 12} = (\text{Die Temp.}) * (\text{Temp. Coefficient}) + K \quad (1)$$

where the die temperature is in units of degrees Centigrade, the temperature coefficient is in units of (Ohms/-degree Centigrade), and K is a minimum resistance in Ohms which circuit **12** has. The temperature coefficient depends upon what material is selected as die thermal sensing circuit **12**, but is conventionally known for a given temperature range. As the die temperature changes, so does the resistance of die thermal sensing circuit **12**. An increase in die temperature causes an increase in the resistance of die thermal sensing circuit **12**, and a decrease in die temperature causes a decrease in the resistance of die thermal sensing circuit **12**. Since the current through the resistance of die thermal sensing circuit **12** is constant, the voltage which is developed across the resistance of die thermal sensing circuit **12** is also proportional to the temperature of the die. In other words, when the die temperature increases the voltage between the first integrated circuit pin **16** and the second integrated circuit pin **18** increases, and vice versa.

In a highly integrated circuit, such as a data processor for example, the amount of electrical current normally channeled to or "sunk" by a ground terminal from the functional operating circuit **14** can be substantial causing the ground potential to actually rise above zero volts. Such an operating condition would therefore create an error voltage between the first integrated circuit pin **16** and the second integrated circuit pin **18**. The error voltage is known in the art by the term "ground bounce".

The present invention however can still be utilized even when ground bounce errors exist. The voltage variation across the resistance of die thermal sensing circuit **12** attributable to ground bounce is common mode with respect to the ground bounce voltage variation at the common or second integrated circuit pin **18**.

Recognizing that the voltage variation due to ground bounce error which occurs across die thermal sensing circuit **12** is common mode makes it possible to eliminate the ground bounce error and thereby use only one dedicated integrated circuit pin for the die thermal sensing. Differential amplifier **24** may be used to subtract the common mode ground bounce noise from the output voltage between integrated circuit pins **16** and **18**. Differential amplifier **24** therefore recovers a pure voltage which is proportional to the resistance of die thermal sensing circuit **12**. In other words, differential amplifier **24** removes a common mode error component from a voltage differential between the first and second integrated circuit pins. Although two integrated circuit pins are utilized, it should be noted that the common or second integrated circuit pin **18** is already present on the integrated circuit and is never taken out of operational use during the die thermal measuring process.

Illustrated in FIG. **2** is a detailed diagram of one form of a differential amplifier which may be used as differential amplifier **24** in connection with constant current source **20** and integrated circuit die **10**. Elements in FIG. **2** which are the same as elements in FIG. **1** are identically numbered for clarification. Differential amplifier **24** has a first operational amplifier **31** having a first, noninverting (positive) input connected to integrated circuit pin **16**. As was illustrated in FIG. **1**, constant current source **20** has the first terminal thereof connected to power supply voltage V_{DD} and the second terminal thereof connected to integrated circuit pin **16** of integrated circuit die **10**. A second, inverting (negative) input of operational amplifier **31** is connected to an output thereof and to a first terminal of a resistor **33**. A second terminal of resistor **33** is connected to a first terminal of a resistor **35**. A second operational amplifier **37** has a first, noninverting (positive) input connected to integrated circuit pin **18** which is a ground terminal on the integrated circuit package and therefore connected to ground. A second, inverting (negative) input of operational amplifier **31** is connected to an output thereof and to a first terminal of a resistor **39**. A second terminal of resistor **39** is connected to a first, noninverting (positive) input of a third operational amplifier **41** and to a first terminal of a resistor **43**. A second terminal of resistor **43** is connected to a ground reference terminal. A second, inverting (negative) input of operational amplifier **41** is connected to both the second terminal of resistor **33** and the first terminal of resistor **35**. A second terminal of resistor **35** is connected to an output of operational amplifier **41** and provides the output voltage Vout. In one form, the three operational amplifiers may be obtained by using the commercially available integrated circuit LF347 from National Semiconductor Corporation which contains four operational amplifiers. A fourth operational amplifier of an LF347 integrated circuit may be used as the constant current source **20**.

In operation, operational amplifiers **31** and **37** are high impedance unity gain buffer stages which do not load integrated circuit pins **16** and **18**. Operational amplifier **41** is configured as a differential amplifier and resistors **33**, **35**, **39** and **43** function to establish a gain of differential amplifier **24**. For example, assume that resis-

tors **33** and **39** have the same resistance, **R1**, and assume that resistors **35** and **43** have the same resistance **R2**. Further assume that the output voltage of operational amplifier **31** is V_R referenced to a ground potential, and that the output voltage of operational amplifier **37** is V_G referenced to the ground potential. The output voltage Vout may therefore be represented as:

$$Vout=[(R2)/(R1)] * [V_G-V_R] \quad (2)$$

where **R1** is the resistance of each of resistors **33** and **39**, and **R2** is the resistance of each of resistors **35** and **43**. As can be seen from equation 2, the ground bounce noise is totally subtracted from the output voltage as a result of the subtraction of V_R from V_G. In other words, each of the V_R and V_G voltages is referenced to ground, and noise bounce which is injected into the ground is therefore neutralized and invisible to the final output voltage provided by differential amplifier **24**.

It should be noted that many integrated circuits have scores of circuit pins in which there is more than one ground reference terminal pin. Any ground reference terminal may be used to implement the present invention but it is preferable to connect differential amplifier **24** to the same ground pin which the die thermal sensing circuit **18** is connected to. If other ground pins are connected to differential amplifier **24** than the ground pin which die thermal sensing circuit **18** is connected to, inductance and other electrical properties may create differential voltage potentials between the various ground circuit pins when the integrated circuit is operational.

The present invention may alternately be used without the assistance of external differential amplifier **24** and constant current source **20**. For example, the resistance of die thermal sensing circuit **12** of integrated circuit die **10** may be measured at room temperature between integrated circuit pins **16** and **18** before the integrated circuit is powered up. Then the integrated circuit may be powered up and is operational for a sufficient amount of time to allow the die to achieve a characteristic operating die temperature. The power should then be disconnected from the integrated circuit and another resistance measurement of the die thermal sensing circuit **12** immediately made. The differing resistance values can be used in accordance with equation 1 to provide an average operating temperature of the integrated circuit. In this technique, ground bounce noise does not exist and is therefore irrelevant.

Thus it is apparent that there has been provided, in accordance with the present invention, an integrated circuit having an on chip thermal circuit requiring only one dedicated integrated circuit pin, and a method of operating the unique integrated circuit. An advantage of the present invention is the saving of an additional dedicated integrated circuit pin to provide a die temperature when the die is powered up and operational. Although the invention has been described and illustrated with reference to specific embodiments thereof, it is not intended that the invention be limited to these illustrative embodiments. For example, one may utilize many different types of die thermal sensing circuit **12** other than a resistor. Further, pins other than the illustrated ground pin which can function as the common integrated circuit pin **18** between the die thermal sensing circuit **12** and other operating circuitry may be used. For example, any fixed voltage potential integrated circuit pin may be used to implement the function of the common integrated circuit pin **18**. It should also be noted that any type of circuitry, whether digital or analog and regardless of process type, may be used as the functional circuitry which is connected to the common integrated circuit pin **18**. Another point which should be noted is that the present invention may be implemented by establishing a fixed voltage across the die thermal sensing circuit **12** and measuring the current thru die thermal sensing circuit **12** which is proportional to die temperature. Although the present invention has been disclosed in the context of a specific differential amplifier structure, other types of differential amplifiers may be used. Those skilled in the art will recognize that modifications and variations can be made without departing from the spirit of the invention. Therefore, it is intended that this invention encompass all such variations and modifications as fall within the scope of the appended claims.

We claim:

1. An integrated circuit having an on chip thermal circuit requiring only one dedicated integrated circuit pin, the integrated circuit comprising:

a die;

a first integrated circuit pin which is dedicated solely for use with the on chip thermal circuit;

a second integrated circuit pin;

an integrated circuit die thermal sensing circuit located on the die and directly connected to the first integrated circuit pin and to the second integrated circuit pin, the integrated circuit die thermal sensing circuit comprising a material which has a physical characteristic which varies in a manner proportional to variation of temperature of the material; and

a functional operating circuit also located on the die and connected directly to the second integrated circuit pin, the functional operating circuit performing a predetermined operating function within the integrated circuit at the same time the integrated circuit die thermal sensing circuit is providing an output signal which indicates an operating temperature of the die;

said second integrated circuit pin being used by both the integrated circuit die thermal sensing circuit and the functional operating circuit.

2. The integrated circuit of claim **1** wherein the integrated circuit die thermal sensing circuit is a resistor.

3. The integrated circuit of claim **2** wherein the resistor is made of metal.

4. The integrated circuit of claim **1** wherein the second integrated circuit pin is a fixed voltage potential terminal.

5. The integrated circuit of claim **4** wherein the fixed voltage potential terminal is a ground reference terminal.

6. The integrated circuit of claim **4** further comprising:

circuitry external to the integrated circuit and connected to the first and second integrated circuit pins, the circuitry measuring a voltage potential between the first integrated circuit pin and the second integrated circuit pin and removing any common mode voltage component coupled to the fixed voltage terminal to provide a voltage which is proportional to the operating temperature of the die.

7. A method of measuring an operating temperature of an integrated circuit die of an integrated circuit re-

sulting from the integrated circuit receiving electrical power, comprising the steps of:

dedicating a single integrated circuit pin solely for use with the method of measuring, the single integrated circuit pin used as a first integrated circuit pin to measure the temperature;

selecting a second integrated circuit pin to use with the first integrated circuit pin, the second integrated circuit pin being used additionally as a functional pin of the integrated circuit concurrent with measuring the temperature;

directly connecting a thermal sensing circuit which is integrated in the integrated circuit die to the first integrated circuit pin and to the second integrated circuit pin, the integrated circuit die thermal sensing circuit comprising a material which has a physical characteristic which varies in a manner proportional to variation of temperature of the material;

directly connecting a functional operating circuit integrated in the integrated circuit die to the second integrated circuit pin, the functional operating circuit performing a predetermined operating function within the integrated circuit; and

concurrent with the functional operating circuit performing the predetermined operating function, providing an output signal between the first integrated circuit pin and the second integrated circuit which is mathematically proportional to the operating temperature of the die.

8. The method of claim **7** wherein the step of connecting an integrated circuit die thermal sensing circuit further comprises:

connecting a resistor directly to the first and second integrated circuit pins.

9. The method of claim **7** wherein the step of selecting a second integrated circuit pin further comprises:

selecting a fixed voltage potential pin of the integrated circuit as the second integrated circuit pin.

10. The method of claim **7** further comprising the step of:

removing a common mode noise error from the output signal before translating the output signal from an electrical value to a temperature value.

11. An integrated circuit having an on chip integrated circuit die thermal circuit, the integrated circuit comprising:

an integrated circuit die;

a first integrated circuit pin which is dedicated solely for use in measuring a temperature of the integrated circuit die when the integrated circuit is receiving electrical power;

a second integrated circuit pin;

a thermal sensing circuit integrated in the integrated circuit die, the thermal sensing circuit having a first terminal directly connected to the first integrated circuit pin and having a second terminal directly connected to the second integrated circuit pin; and

circuitry connected directly to the second integrated circuit pin, the circuitry being operational and utilizing the second integrated circuit pin concurrently while the first and second integrated circuit pins are used to provide a signal which is proportional to the temperature of the integrated circuit die.

12. The integrated circuit of claim **11** wherein the thermal sensing circuit is a resistor made of a material consisting of one of: polysilicon and metal.

13. The integrated circuit of claim **11** further comprising:

a constant current source external to the integrated circuit for providing a reference current to the first integrated circuit pin; and

a differential amplifier external to the integrated circuit and connected to the first and second integrated circuit pins, the differential amplifier removing a common mode error component from a voltage differential between the first and second integrated circuit pins.

14. The integrated circuit of claim **11** further comprising:

circuitry connected to the first and second integrated circuit pins, the circuitry removing a common mode noise error from the signal which is proportional to the temperature of the integrated circuit before translating the signal from an electrical value to a temperature value.

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